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Game-Theoretic Models for Electric Distribution Resiliency/Resiliency from a Multiple Stakeholder Perspective

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Abstract - We study decentralized decisions among resiliency investors for hardening electric distribution systems with governance, which could coordinate the achievement of social optimums. Significant investments are being made to build resilient infrastructure for society well-being by hardening electric distribution networks. However, whether independent investment decisions can reach social optimums are not well-studied. Previous research has focused on optimization of system designs to improve resiliency with limited modeling efforts on the interactions of decentralized decision making. Within regulatory governance, we investigate interactions between two independent resiliency investors with a game-theoretic model incorporating detailed payoff functions. Moreover, we demonstrate the framework with typical data and sensitivity analyses. We find that the decentralized optimal solution is not a social optimum without governance and the government could subsidize grid hardening to achieve the social optimum. Additionally, we conduct Monte-Carlo simulations by varying key parameters and find that a socially undesirable outcome could occur with the highest frequency. Therefore, it is important to narrow the uncertain ranges for particular benefits/costs and use policy instruments to induce the socially desired outcomes. These results yield important insights into the role of regulatory governance in supervising resiliency investors and highlight the significance of studying the interactions between independent investors.

Keywords: electricity distribution resiliency; game theory; regulatory governance

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1. Introduction

In this research effort, we focus on one important aspect of resiliency and reliability improvement investments, namely, the interactions between independent investors (e.g., public versus private) within the context of regulatory governance. Regulatory governance is defined as "the capacity to manage resources efficiently and to formulate, implement, and enforce sound prudential policies and regulations" (Das et al., 2004).

In particular, we develop game-theoretic models with detailed payoff functions to better understand and quantify the strategic interactions between two independent investors of resiliency/reliability improvement of electric distribution systems allowing the presence of regulatory governance. It is important to consider the role of government, especially regulatory governance, within the context of this analysis. This is because the government could deploy regulatory power to improve social welfare, which might not be achievable without government intervention.

Reliability of electric distribution systems refers to the susceptibility of the systems to interruptions that cause outages. Within the following analysis, a reliable electric distribution system has few outages. That is, we operationally define a reliable electric distribution system as less likely to experience an outage (i.e., a hardened grid is less likely to experience an outage than an unhardened grid). There are also several other popular definitions of reliability. For example, the North American Electric Reliability Council (NERC) defines reliability as "the degree to which the performances of the elements of [the electrical] system result in power being delivered to consumers within accepted standards and in the amount desired" (Hirst and Kirby, 2000). The two concepts of adequacy and security are both included in this definition (NERC, 1997). Another well-known definition of reliability is "the probability that the system is able to retain, over a given time period, its intended function under given conditions when it is subject to internal or external failures" (Mili, 2011). There are several different definitions of resiliency, with subtle differences. Mili (2011) defines resiliency as "the ability of this system to (i) gracefully degrade its function by altering its structure in an agile way when it is subject to a set of unexpected extreme perturbations and (ii) quickly recover it once the perturbations ceased". For others, "resiliency is defined as the ability of a system to return to its original state after being disturbed. … Resiliency refers to the ability to quickly return to a 'business as usual' state after a natural disaster or other event causing

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an electric grid outage" (ICF International, 2013). In the model (CERT-RMM) proposed by Caralli, Allen and White (2010), "CERT-RMM defines resilience as the emergent property of an organization that can contribute to carry out its mission after disruption that does not exceed its operational limit." Lastly, Sandia National Labs (2015) claim "a resilient electric infrastructure would be able to react predictively to threats and adjust to disasters before they happen". In this paper, resiliency is defined as the ability to rebound quickly to the original state given a major interruption in the electric power grid. In particular, after resiliency improvement initiatives (e.g., installation and operation of combined heat and power (CHP) with blackstart capability), the associated private facility no longer suffers from power outages due to natural disasters, such as hurricanes. Resiliency and reliability are two distinct concepts and their improvement initiatives could have different effects on the operations of the electric power system. With combined efforts to improve its reliability and resiliency, an electric distribution system could not only enhance its dependability in supplying electricity but also recover quickly after outages.

Extreme weather events such as hurricanes are projected to increase in intensity with high likelihood due to climate change (USGCRP, 2009). Hurricanes have significantly challenged public infrastructures in North America. For instance, New Jersey was heavily impacted by Superstorm Sandy, which resulted in almost three million residents without power for six days or more, and caused damage to 100 high voltage electricity transmission lines and more than 4,000 electric utility transformers (Johnson, 2014). It is imperative to improve the resiliency of the electric power grid before the next extreme weather event occurs. Federal, state, and local governments are providing significant funds to support resiliency/reliability enhancing measures by electric utilities responsible for upgrading critical infrastructure and private sector owners who can build resiliency into their systems (e.g., Barber, 2014; Johnson, 2014).

In this paper, we develop sequential and simultaneous game-theoretic models to better understand and quantify the strategic interactions between those independent investors (i.e., electric utilities and persons who own particular facilities such as private manufacturing factories, which in contrast to public facilities include highways and bridges). Our goal is to study whether those decentralized optimal decisions can achieve social optima, and to define the government's role in facilitating a win-win situation, where every party improves over the case without governance. Specifically, with a realistic numerical example, we study whether 1) regulating the

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order of decision making between those two independent investors, and 2) incentivizing CHP and/or grid hardening could achieve social optima. This research bears significant practical implications and can potentially lead to more efficient usage of limited resiliency resources.

2. Background

There are four primary components of an electric grid: electricity generation, transmission, distribution, and load. Most outages during weather extremes are due to failure in the electricity distribution (OFGEM, 2009). Distributed generation and electric grid hardening provide two solutions to grid outages from weather extremes. Distributed generation involves the use of smaller generation units that are located closer to or are co-located with the customers of electricity. Only distributed generators (DG) such as CHPs that are equipped with blackstart capability would enhance resiliency of a power network, because when the grid is down, only DGs that are equipped with blackstart capability can operate. Blackstart capability refers to "the ability of a CHP system to independently start on its own without receiving any power from the grid. This can be achieved by way of a battery powered starting device or a backup generator" (Athawale and Felder, 2014).

2.1 Private and public investments to improve resiliency/reliability with governance

DGs represent typical private investments to enhance the resiliency of electric systems. CHP is one type of distributed power generation, which can generate electricity and useable heat simultaneously, and in general, provide more energy efficiency than generators on the grid. CHP saves the owners energy costs and brings environmental and health benefits to society (see Athawale and Felder for detailed descriptions of CHPs, 2014). Moreover, with an additional investment, CHP could be enabled with blackstart capability and run in island mode when the electric power grid is down, enhancing grid resiliency for the owner in terms of continuous operation during grid outages. There are mainly two ways that CHP with blackstart capability enhances grid resiliency. First, during a major interruption to the electric power grid, the misalignment of demand and residual supply decreases grid resiliency. CHP running in island mode could supply its own electricity needs and thus reduce the burden on the electric power grid to supply electricity to its associated facility. Second, it provides essential electric service to its owner for continuous operations following natural disasters, such as hurricanes. For a CHP to provide a resiliency benefit, the capital cost of additional investment for blackstart capability is necessary. Some benefits of a CHP with blackstart capability include avoided productivity loss and equipment damage. The

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net of benefits and costs will affect the cost-effectiveness of a particular CHP.

Grid hardening is the electric utility's action on behalf of its customers to improve the resiliency and/or reliability of electric supply and is defined as strategies implemented to improve resiliency and/or reliability of electric power distribution systems. Research on how to improve electric power grid reliability has led to numerous publications (see Billinton and Allan for review, 1992). Many researchers take optimization approaches and consider reliability from a single decision maker's perspective. For example, Coit and Smith (1996) developed a problem-specific genetic algorithm to analyze series-parallel systems and then identified the optimal system design. Recently, the optimization problem designed for reliability improvements has become more complicated and specific (Xiang et al., 2013; Liu et al., 2014; Rafiee et al., 2014). Some grid hardening initiatives such as elevation and relocation of switching stations and substations might improve the reliability of the electric power grid more than its resiliency whereas others, including deployment of smart-grid technology to improve system monitoring, could enhance the resiliency of the electric power grid more than its reliability (EPRI, 2013; Friedman, 2014).

Governance plays a major role in regulating electricity markets, as well as facilitating and coordinating the work of independent system operators to increase the well-being of the society (Felder, 2012). Appropriate levels of structured governance are especially needed for evolving electric markets during a time of expansion and reorganization (Felder, 2002). Another critical reason for the necessity of governance is due to the fact that independent decision making among stakeholders, occurring without government intervention, might not achieve social optima. The government is playing the central role of encouraging both public and private investors to enhance resiliency and energy efficiency, which are two main objectives. As an example of a utility's investments on behalf of its customers, the Board of Public Utility in the state of New Jersey recently approved a proposal for the "Energy Strong" program by PSE&G, a major electric utility in the state; this program mainly involves electric power grid hardening, and costs ratepayers $1.2 billion (Friedman, 2014). Meanwhile, governments are also incentivizing private investments to improve resiliency of electric infrastructure, typically by providing subsidies and tax benefits to private purchases and installation of CHPs (ACEEE, 2014). However, little is known about the possible strategic interactions between these seemingly parallel decision processes. Given that there is overlap in the beneficiaries from more resilient/reliable electric infrastructure, interactions between electric

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utilities and persons who own particular facilities such as private manufacturing factories, which are in contrast to public facilities including highways and bridges, are expected but not well understood. Specifically, whether the possible interactions from the two independent decision makers could lead to social optima is not well studied, but is of vast public interest. In addition, government is expected to play a major role in fostering resiliency/reliability improvement initiatives, which might be impaired without sufficient knowledge of the interactions. Besides providing incentives, government also may have the regulatory authority to participate in determining whether a resiliency/reliability project can start, and thus, could more effectively coordinate public and private investments in resiliency/reliability.

2.2 Literature review

Power planning models have increasingly incorporated environmental considerations and reliability constraints. Hobbs (1995) presented a review of optimization methods developed for all stages of electric resource planning including long-term capital planning and short-term operation planning. Kagiannas et al. (2004) conducted another review focusing on generation planning methods developed for a competitive electricity generation market. Reliability constitutes a main constraint in generation expansion planning (GEP) (Chuang et al. 2001; Jenabi et al. 2013). Chuang et al. (2001) addressed reliability issues for the electric generation part of the electric grid, while the current paper considers resiliency and reliability from the distribution perspective.

Game theory is useful for studying the strategic interactions between multiple decision makers with conflicting interests (Shan and Zhuang, 2013 a,b; 2014 a,b). Game-theoretic research has been devoted to studying market power within the context of possible governance (Hobbs et al., 2000; Duke and Geurts, 2004; Gabriel and Leuthold, 2010; Siddiqui and Gabriel, 2013). Further, Lo Prete and Hobbs (2016) employed cooperative game theory to study a possible coalition among three players: utility company, microgrid developer, and customers. This paper and the associated research address the strategic interactions between multiple decision makers when addressing resiliency/reliability issues together within the context of regulatory governance. The rest of the paper is structured as follows. Section 3 presents the modeling framework and solutions for the two sequential games, where either a private investor or a utility investor on behalf of its customers of resiliency/reliability improvement initiatives decides first. The results are compared with the case where government intervention is introduced (e.g., encourage the utility to harden the electric power grid when the private investor invests in a CHP) and analytical sensitivity analyses are conducted. We also consider a simultaneous game, where the two investors decide without knowing each other's decision. Section 4 demonstrates the modeling framework with a realistic numerical example to demonstrate what might happen in practice, and includes empirical sensitivity analyses and Monte Carlo simulations with regard to key parameters. Section 5 concludes and provides future research directions.

3. Modeling framework

In this section, we first present the modeling approach, its justification, and significance. Second, we explain our models in detail. Finally, examples of the solution are given with analytical sensitivity analyses and discussion of the solution. This new model introduces two players in sequential and simultaneous games, defined as *utility* and *factory*, which is one of two main customers served by *utility*. *Utility* distributes electricity to a region and its customer base consists of *factory* and the rest (i.e., the other customer). Note that the other customer represents a group of residential, commercial, and industrial customers (or any mix thereof); it is a passive observer who does not make decisions. The model is intended to quantify the strategic interactions between *factory* and *utility* within the context of regulatory governance, which could 1) influence the decisions of *factory* and *utility*, 2) determine the sequence of decision making between *factory* and *utility* (*factory* or *utility* moves first or simultaneously), and 3) subsidize CHP investments and/or grid hardening.

3.1 Modeling approach

The research scope is to investigate the role of governance in interactions between two main decision makers in electric distribution systems, representing utility and private investors who improve the resiliency of electricity supply. One general approach is to study if the sequence of decision making (i.e., either player moves first or simultaneously) results in a meaningful difference in terms of equilibrium solutions. Then, we evaluate the equilibrium solutions in terms of social costs to study whether government, representing the society, has an incentive to regulate the sequence of decision making. Also, we compare the sequential games with a simultaneous game. While some degree of simplification is necessary to maintain tractability of the solutions, the simplified model exemplifies our best efforts to represent reality, and the basic framework remains the same as new benefit/cost terms are added to the payoff structures. With the modeling framework, we are able to identify conditions favoring government intervention and socially desirable outcomes.

Regarding the status quo of the current process for the utility to choose whether to harden the grid and the factory to choose whether to invest in CHP, these processes are not necessarily uniform throughout the United States because they depend in part on state policies. Major utility hardening decisions may require prior approval by the public utility commission that regulates the utility and may even be a utility's response to calls from that commission to harden the grid. Such major initiatives would trigger public notification and an open hearing process by commissions, thus informing, perhaps partially, factories that are considering CHP facilities. In addition, some states provide financial support to build CHP facilities, and the associated process and awards may also become public. Thus, depending on various state policies, having a simultaneous game, i.e., neither utility nor factory know about the decision of the other party, may not be possible. Commissions, on the other hand, may have control on the sequencing of decisions regarding utility hardening and awarding financial incentives to CHP.

3.2 Sequential games

In this section, we study two sequential games between *utility* and *factory*. The decision problem for *factory* is whether to invest in a CHP, and then if the given CHP is purchased, whether to enable it with blackstart capability. The decision problem for *utility* is whether to harden the grid. The objective of *factory* is to minimize costs associated with CHP, energy cost, and outage cost due to operation interruption, whereas *utility* aims to maximize revenues from electricity sales minus the cost of grid hardening. We label the game where *factory* decides first as Game I and the game where *utility* decides first as Game II. We assume that government could decide which game *factory* and *utility* should play (Games I or II). The objective of the government is to minimize the energy cost of *factory* and the cost of grid hardening, the capital cost of a CHP or a CHP with blackstart capability, and loss caused by outages (either from a hardened grid or a CHP with blackstart capability). The payoffs representing players' objectives are presented in Section 3.4. Problem parameters and notation are presented in Table 1. If *utility* hardens the grid, the cost will be shared among all customers including *factory* and will be recovered by return over time (including *utility*'s cost of capital). For simplicity, we assign a one-time cost to *factory* (c_H) instead of additional payments through a tariff increase. The size of the grid is 25,300 kW, which is the sum of demands by *factory* and the other customer. The assumed capital cost to enable a CHP generator with blackstart capability is \$0.13 million, which is the difference of investing in a CHP with or without blackstart capability.

Figure 1 shows the game trees for the two games where either *factory* (Game I) or *utility* (Game II) decides first. We assume the games are non-cooperative, with perfect and complete information. In Game I, *factory* decides first by choosing among three options: not investing in a CHP (No CHP), investing in a CHP (CHP), and investing in a CHP with blackstart capability (CHP+B/S). After observing *factory*'s decision, *utility* decides whether to harden the grid (Not Harden or Harden). By contrast, in Game II, *utility* becomes the first decision maker and decides whether to harden the grid. After observing *utility*'s decision, *factory* chooses among the three options: No CHP, CHP, and CHP+B/S.

3.3 Simultaneous game

We also study a simultaneous game between *factory* and *utility*. This game could represent the baseline case, where neither *utility* nor *factory* makes its own decision without the information about the other player's decision. It could serve as a regulatory option for the government but is difficult to achieve.

3.4 Payoffs of *utility*, *factory*, and *society*

The six outcomes of the sequential and simultaneous games are designated as Case $1/\bar{C}/\bar{H}$ to Case $6/B/H$ as indicated in Figure 1. Case $1/\bar{C}/\bar{H}$ denotes the outcome that *factory* does not invest in a CHP (No CHP) and *utility* chooses not to harden the grid (Not Harden). Case $2/\bar{C}/H$ denotes the outcome that *factory* does not invest in a CHP (No CHP) and *utility* chooses to harden the grid (Harden). Case $3/C/\bar{H}$ denotes the outcome that *factory* invests in a CHP (CHP) and *utility* chooses not to harden the grid (Not Harden). Case $4/C/H$ denotes the outcome that *factory* invests in a CHP (CHP) and *utility* chooses to harden the grid (Harden). Case $5/B/\bar{H}$ denotes the outcome that *factory* invests in a CHP with blackstart capability (CHP+B/S) and *utility* chooses not to harden the grid (Not Harden). Case $6/B/H$ denotes the outcome that *factory* invests in a CHP with blackstart capability (CHP+B/S) and *utility* chooses to harden the grid (Harden).

The same set of six outcomes can be reached in all three games (two sequential games and one simultaneous game). For instance, if *factory* moves first and invests in a CHP and *utility* responds by hardening the grid in

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Game I, Case $4/C/H$ is reached. If they are playing Game II instead, *utility* moves first and hardens the grid and *factory* responds by investing in a CHP, and Case $4/C/H$ is again reached. If *factory* invests in a CHP and *utility* hardens the grid simultaneously, Case $4/C/H$ is still reached.

Table 2 presents the payoffs for *factory*, *utility,* and *society* of the six cases in Figure 1. Payoff is interpreted as cost minus benefit (e.g., benefit of net emission reductions is explicit in the payoff for *society,* whereas the benefit of grid hardening or investing in a CHP with/without blackstart capability is implicit and reflected in cost/loss reduction). We also assume that for the other customer, annual consumption of electricity is e^W, average hourly demand is D^W, and its VOLL minus electricity tariff is $V^W(l) - f$.

3.4.1 *Factory*'s payoffs

If *factory* does not invest in CHP, *factory*'s payoff is the sum of net present values (NPVs) of energy costs and outage costs over the planning horizon of 20 years. By contrast, if *factory* invests in CHP, *factory*'s payoff includes NPVs of the capital (in Year 0; minus government's incentive) and variable costs (Years 1-20) of CHP as well. Note that the energy cost in Year 0 is different from that in Years 1-20 if *factory* invests in CHP. Further, if factory invests in CHP with blackstart capability, *factory*'s payoff includes no outage costs but the operating cost of CHP during outages. On the other hand, if *utility* hardens the grid, *factory*'s payoff includes its contribution to pay for the cost of grid hardening. Note that we assume that *factory* and the other customer pay for the cost of grid hardening through one-time contributions, which are equivalent to a tariff increase. The equations for *factory*'s payoffs are presented in Table 2.

3.4.2 *Utility*'s payoffs

If *utility* does not harden the grid, *utility*'s payoff is the sum of NPVs of electricity sales to *factory* and the other customer. By contrast, if *utility* hardens the grid, *utility*'s payoff also includes the capital cost of grid hardening minus the return over time allowed by the government besides revenues from electricity sales. Note that if *factory* invests in CHP, electricity sales to *factory* will decrease. The equations for *utility*'s payoffs are presented in Table 2. Note that revenues are computed for *utility*. To maintain consistency in computing payoffs, we convert *utility*'s revenues to costs by multiplying with -1.

3.4.3 *Society*'s payoffs

To compute payoffs for *society* in Table 2, we sum payoffs for *factory* and *utility* excluding *factory*'s contribution and return over time to the cost of grid hardening, revenues from electricity sales by *utility* to *factory*, and incentive for CHP, as well as adding outage loss to the other customer (i.e., $V^W(l) - f$). Note that return over time (a tariff increase) to the cost of grid hardening is canceled out with *factory*'s and the other customer's contributions. Also, on the *society*'s payoff in Year 0, e is the cost of real societal resources to generate and transmit electricity from *utility* to *factory*. Similarly, the cost of real resources to *society* in Year 1 to generate and transmit electricity from *utility* to *factory* is e_c. As a result, e and e_c are included in *society*'s payoff to represent the associated real societal costs. We assume that the cost of real societal resources equals *factory*'s cost of purchasing electricity from *utility*. As an example to explain the payoff functions for the three parties, Figure 4 illustrates the payoffs for *factory*, *utility,* and *society* in Case $6/B/H$ (*factory* invests in a CHP with blackstart capability and *utility* hardens the grid) from Table 2, which shows both benefits/costs of grid hardening and CHP with blackstart capability.

Comparing the other five cases with Case $6/B/H$ in Figure 4 and Table 2, the differences are as follows. In Case $1/\bar{C}/\bar{H}$, there are 4 differences with Case $6/B/H$ for *factory*'s payoff: 1) there is no capital costs of investments in CHP with blackstart capability (minus incentive) or contribution to grid hardening (i.e., there is no $b - i + c_H$); 2) the probability of outages changes (from p_H to p_N); 3) the probability of normal operation changes as a result of a change in the probability of outages (from $\frac{\sum_l p_H^l(M-l)+(1-\sum_l p_H^l)M}{M}$ to $\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}$); 4) in Years 1-20, the energy cost changes from $e_c + g_c + S(h_o, D) + c_o(h_o) - un(h_o)$ to $e + g$ due to the absence of CHP; and 5) during outages in Years 1-20, instead of running CHP in island mode with a cost of $g_c^b(l) + c_o(h_o)$, *factory* suffers a VOLL of $l[D(V(l) - f)]$. There are three differences with Case $6/B/H$ for *utility*'s payoff: 1) there is no capital cost and return over time of grid hardening ($K - \sum_t FK(1-d)^t$); 2) the probability of normal operation changes as a result of a change in probability of outages (from $\frac{\sum_l p_H^l(M-l)+(1-\sum_l p_H^l)M}{M}$ to $\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}$); and 3) in Years 1-20, the electricity sales change due to increase in electricity consumption without CHP (from e_c to e). There are five differences with Case $6/B/H$ for *society*'s payoff: 1) there are no capital costs for grid hardening and CHP with blackstart capability (i.e., there is no $b + k$); 2) the probability of outages changes (from p_H to p_N); 3) the probability of normal operation changes as a result of a change in the probability of outages (from $\frac{\sum_l p_H^l(M-l)+(1-\sum_l p_H^l)M}{M}$ to $\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}$); 4) in Years 1-20, the energy cost changes from $e_c + g_c + S(h_o, D) + c_o(h_o) - un(h_o)$ to $e + g$ due to the absence of CHP; and 5) during outages in Years 1-20, instead of running CHP in island mode with a cost of $g_c^b(l) + c_o(h_o)$, *factory* suffers a VOLL of $l[D(V(l) - f)]$.

In Case $2/\bar{C}/H$, there are three differences with Case $6/B/H$ for *factory*'s payoff: 1) there is no capital cost of CHP with blackstart capability minus incentive ($b - i$); 2) in Years 1-20, the energy cost changes from $e_c + g_c + S(h_o, D) + c_o(h_o) - un(h_o)$ to $e + g$ due to the absence of CHP; 3) during outages in Years 1-20, instead of running CHP in island mode with a cost of $g_c^b(l) + c_o(h_o)$, *factory* suffers a VOLL of $l[D(V(l) - f)]$. There is one difference with Case $6/B/H$ for *utility*'s payoff: in Years 1-20, the electricity sales change due to increase in electricity consumption without CHP (from e_c to e). There are three differences with Case $6/B/H$ for *society*'s payoff: 1) there is no capital cost of CHP with blackstart capability (b); 2) in Years 1-20, the energy cost changes from $e_c + g_c + S(h_o, D) + c_o(h_o) - un(h_o)$ to $e + g$ due to the absence of CHP; and 3) during outages in Years 1-20, instead of running CHP in island mode with a cost of $g_c^b(l) + c_o(h_o)$, *factory* suffers a VOLL of $l[D(V(l) - f)]$.

In Case $3/C/\bar{H}$, there are four differences with Case $6/B/H$ for *factory*'s payoff: 1) there is no cost of contribution to grid hardening and *factory* invests in CHP without blackstart capability (i.e., *c* instead of $b + c_H$); 2) the probability of outages changes (from p_H to p_N); 3) the probability of normal operation changes as a result of a change in the probability of outages (from $\frac{\sum_l p_H^l(M-l)+(1-\sum_l p_H^l)M}{M}$ to $\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}$); and 4) during outages in Years 1-20, instead of running CHP in island mode with a cost of $g_c^b(l) + c_o(h_o)$, *factory* suffers a VOLL of $l[D(V(l) - f)]$. There are two differences with Case $6/B/H$ for *utility*'s payoff: 1) there is no capital cost and return over time of grid hardening ($K - \sum_t FK(1-d)^t$); and 2) the probability of normal operation changes as a result of a change in the probability of outages (from $\frac{\sum_l p_H^l(M-l)+(1-\sum_l p_H^l)M}{M}$ to $\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}$). There are four differences with Case $6/B/H$ for *society*'s payoff: 1) there is no capital costs of investments in grid hardening and *factory* invests in CHP without blackstart capability (i.e., *c* instead of $b + K$); 2) the probability of outages changes (from p_H to p_N); 3) the probability of normal operation changes as a result of a change in the probability of outages (from $\frac{\sum_l p_H^l(M-l)+(1-\sum_l p_H^l)M}{M}$ to $\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}$); and 4) during outages in Years 1-20, instead of running CHP in island mode with a cost of $g_c^b(l)+c_o(h_o)$, *factory* suffers a VOLL of $l[D(V(l)-f)]$.

In Case $4/C/H$, there are two differences with Case $6/B/H$ for *factory*'s payoff: 1) there is no additional capital cost of blackstart capability (i.e., *c* instead of b); and 2) during outages in Years 1-20, instead of running CHP in island mode with a cost of $g_c^b(l)+c_o(h_o)$, *factory* suffers a VOLL of $l[D(V(l)-f)]$. There is no difference with Case $6/B/H$ for *utility*'s payoff. There are two differences with Case $6/B/H$ for *society*'s payoff: 1) there is no additional capital cost of blackstart capability (i.e., *c* instead of b); and 2) during outages in Years 1-20, instead of running CHP in island mode with a cost of $g_c^b(l)+c_o(h_o)$, *factory* suffers a VOLL of $l[D(V(l)-f)]$.

In Case $5/B/\bar{H}$, there are three differences with Case $6/B/H$ for *factory*'s payoff: 1) there is no cost of contribution to grid hardening (i.e., there is no c_H); 2) the probability of outages changes (from p_H to p_N); and 3) the probability of normal operation changes as a result of a change in the probability of outages (from $\frac{\sum_l p_H^l(M-l)+(1-\sum_l p_H^l)M}{M}$ to $\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}$). There are two differences with Case $6/B/H$ for *utility*'s payoff: 1) there is no capital cost and return over time of grid hardening ($K-\sum_t FK(1-d)^t$); and 2) the probability of normal operation changes as a result of a change in probability of outages (from $\frac{\sum_l p_H^l(M-l)+(1-\sum_l p_H^l)M}{M}$ to $\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}$). There are three differences with Case $6/B/H$ for *society*'s payoff: 1) there are no capital cost for grid hardening (*K*); 2) the probability of outages changes (from p_H to p_N); 3) the probability of normal operation changes as a result of a change in the probability of outages (from $\frac{\sum_l p_H^l(M-l)+(1-\sum_l p_H^l)M}{M}$ to $\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}$).

Together with Figure 4, the differences are specified to assist in understanding Table 2. Detailed calculations are based on Athawale and Felder (2014). We explain one example of emission reductions. Non-CHP facilities cause emissions in two ways: from thermal boilers and generators (based on fuel type). Avoided electricity purchase with CHP allows us to calculate how much less air emissions were achieved due to using CHP to

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displace some generators on the grid.

To obtain the decentralized optimal solution to the games, we make five major assumptions as follows:

1. Running a CHP is less expensive than relying on the grid for electricity

$$e + g - e_c - g_c - S\big(h_o,\, D\big) - c_o(h_o) > 0$$

2. During l-hour outages, operating a CHP with blackstart capability is cheaper than the outage cost for l-hour interruption

$$lD(V(l) - f) - (g_c^b(l) + S\big(h_o,\, D\big) + c_o(h_o)) > 0$$

3. Cost of annual electricity (gas) consumption is lower (higher) with a CHP than that without a CHP

$$e > e_c, \qquad g < g_c$$

4. Probability of outages after *utility* hardens the grid is lower than if nothing is done

$$p_N^l > p_H^l$$

5. Capital cost of a CHP with blackstart capability is higher than capital cost of a regular CHP

$$b > c$$

3.5 Examples of a solution to sequential games and discussion

To illustrate the solution processes, Sections 3.5.1 and 3.5.2 present examples of a solution to Games I and II (as in Figure 1), respectively. Furthermore, we also compare *soceity*'s payoffs between a (decentralized) optimal solution and two non-optimal but socially-desirable outcomes.

3.5.1 Game I and its solution

We first solve Game I using backward induction and find three conditions for a specific case to achieve equilibrium. If any of the three conditions does not hold, the solution changes. Section 3.7 demonstrates how the solution changes in three key parameters. We chose the three conditions to correspond to the values of capital costs of grid hardening (K), CHP (c), and CHP with blackstart capability (b) since those values could be influenced by a government's subsidy, which can be a governance policy instrument that facilitates and coordinates the achievement of social optima.

The equilibrium solutions differ depending on the values of K, c and b with regard to some thresholds. To quantify those thresholds, we define some new notation as follows (also listed in Table 1). The threshold for K is denoted by $T_K^{\alpha\beta}$, which equals *utility*'s payoff in Case α minus the *utility*'s payoff in Case β plus K. If in Case α, *utility* does not harden the grid, and in Case β, it does, then $T_K^{\alpha\beta}$ represents the benefit of hardening the grid to *utility*. This is because *utility* in Case β makes more profit (*utility*'s payoff is more negative) than *utility* in Case α. As a result, *utility*'s payoff in Case α (not hardening the grid) *minus* the *utility*'s payoff in Case β (hardening the grid) represents the additional profits that *utility* can make if *utility* hardens the grid. That is, if *utility* hardens the grid, the probability of outage decreases (from p_N^l to p_H^l) and thus the probability of normal operation increases $\left(\text{from } \frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M} \text{ to } \frac{\sum_l p_H^l(M-l)+(1-\sum_l p_H^l)M}{M}\right)$. As a result, the *utility* would make higher profits in Case β (hardening the grid). Note that α/β refer to particular case identities as in Table 1 and α (and β) can represent any of the six cases. Similarly, the threshold for c (or b) is denoted by $T_c^{\alpha\beta}$ (or $T_b^{\alpha\beta}$), which equals *factory*'s payoff in Case α minus that in Case β plus c (or b). For example, if in Case α, *factory* does not invest in a CHP, and in Case β, it does, then $T_c^{\alpha\beta}$ represents the benefit of investing in a CHP to *factory*. As a result, the net benefit of hardening the grid to *utility* is represented by $T_K^{\alpha\beta} - K$. Similarly, the net benefit of investing in a CHP to *factory* is represented by $T_c^{\alpha\beta} - c$, whereas the net benefit of investing in a CHP with blackstart capability to *factory* is represented by $T_b^{\alpha\beta} - b$.

In summary, thresholds for equilibrium conditions are defined below:

$$T_K^{\alpha\beta} = (Utility \text{ Payoff in Case } \alpha) - (Utility \text{ Payoff in Case } \beta) + K$$

$$T_c^{\alpha\beta} = (Factory \text{ Payoff in Case } \alpha) - (Factory \text{ Payoff in Case } \beta) + c$$

$$T_b^{\alpha\beta} = (Factory \text{ Payoff in Case } \alpha) - (Factory \text{ Payoff in Case } \beta) + b$$

The detailed solution process for one example of a solution is as follows:

<u>Step 1</u>: we solve Subgame I by comparing *utility* payoffs for Cases $1/\bar{C}/\bar{H}$ and $2/\bar{C}/H$. The difference (Case $1/\bar{C}/\bar{H}$ subtracting Case $2/\bar{C}/H$) is $T_K^{12} - K$. Therefore, if $K < T_K^{12}$ (payoff in Case $1/\bar{C}/\bar{H}$ is higher than payoff in Case $2/\bar{C}/H$), Case $2/\bar{C}/H$ is preferred by *utility* over Case $1/\bar{C}/\bar{H}$ and solves Subgame I. <u>Step 2</u>: we solve Subgames II and III (they are identical for *utility*) by comparing *utility* payoff for Case $3/C/\bar{H}$ and $4/C/H$ (Cases $5/B/\bar{H}$ and $6/B/H$). The difference (Case $3/C/\bar{H}$ subtracting Case$4/C/H$) is $T_K^{34} - K$. Therefore, if $K > T_K^{34}$, Case $3/C/\bar{H}$ ($5/B/\bar{H}$) solves Subgame II (III). Note that *utility* payoff in Case $3/C/\bar{H}$ ($4/C/H$) is the

same as in Case $5/B/\bar{H}$ $(6/B/H)$. Therefore, we have $T_K^{34} = T_K^{56}$. Step 3: we compare *factory* payoffs for Cases $2/\bar{C}/H$, $3/C/\bar{H}$, and $5/B/\bar{H}$. The difference (Case $2/\bar{C}/H$ subtracting Case $3/C/\bar{H}$) is $T_c^{23} - c$. The difference (Case $2/\bar{C}/H$ subtracting Case $5/B/\bar{H}$) is $T_b^{25} - b$. Therefore, if $c > T_c^{23}$, and $b > T_b^{25}$, Case $2/\bar{C}/H$ wins over Cases $3/C/\bar{H}$ and $5/B/\bar{H}$.

In sum, if $T_K^{34} < K < T_K^{12}$, $c > T_c^{23}$, and $b > T_b^{25}$, Case $2/\bar{C}/H$ is optimal to Game I. This solution implies that if the capital costs for grid hardening (K), a CHP (c), and a CHP with blackstart capability (b) are modest, the decentralized optimal solution to Game I in Figure 1 proves to be Case $2/\bar{C}/H$ (*factory* does not invest in a CHP and *utility* hardens the grid). Note that we selected this scenario because the order of who moves first affects the decentralized optimal solution under this scenario, and *society* could have a different preference than *factory* and *utility*, which depends on factors such as value of emission reductions. In addition, we observe that there are complicated relationships between thresholds for *factory* and *utility*. For example, T_c^{23} is determined both by the grid hardening benefit and cost to *factory* and the benefit from running a CHP in terms of energy savings, among other factors.

However, the decentralized optimal outcome for *factory* and *utility* might not be optimal for *society*. *Society* would prefer not only resiliency but also energy efficiency and thus emission reductions, which are achieved in Cases $4/C/H$ and $5/B/\bar{H}$. *Society*'s payoff in Case $2/\bar{C}/H$ is larger than that in Case $4/C/H$ by the following amount:

$$\underbrace{-c}_{\text{Cost of CHP}} + \underbrace{\left(\frac{\sum_l p_H^l (M-l) + \left(1-\sum_l p_H^l\right)M}{M}\right)\left[(e+g) - \left(e_c + g_c + S(h_o, D) + c_o(h_o) - un(h_o)\right)\right]}_{\text{Benefit of CHP on normal energy consumption}}$$

A positive difference implies that *society*'s payoff (cost) is higher in Case $2/\bar{C}/H$ than *society*'s payoff (cost) in Case $4/C/H$ and society would prefer Case $4/C/H$. By examining the difference in payoff, we observe that when the benefits of energy saving ($(e+g) - \left(e_c + g_c + S(h_o, D) + c_o(h_o)\right)$ and emission reductions ($un(h_o)$) by using a CHP are sufficiently large compared to the cost of CHP, *society* would prefer Case $4/C/H$. On the other hand, *factory*'s payoff is only affected by the benefit of energy saving ($(e+g) - \left(e_c + g_c + S(h_o, D) + c_o(h_o)\right)$ from using a CHP whereas the magnitude of emission reduction ($un(h_o)$) is not expected to affect *utility*'s decision.

Similarly, the difference in *society*'s payoffs between Case $2/\bar{C}/H$ and Case $5/\mathrm{B}/\bar{\mathrm{H}}$ (Case $2/\bar{C}/H$ minus Case $5/\mathrm{B}/\bar{\mathrm{H}}$) mainly consist of (1) the difference between the cost of hardening the grid and the cost of CHP with blackstart capability ($K - b$), (2) energy savings ($e + g - (e_c + g_c + S(h_o, D) + c_o(h_o))$), (3) emission reductions ($un(h_o)$), (4) the VOLL for *factory* ($D(V(l) - f)$), and (5) the benefit of grid hardening ($p_N^l - p_H^l$). Note that (2) and (3) are due to using CHP in Case $5/\mathrm{B}/\bar{\mathrm{H}}$; (4) only exists in Case $2/\bar{C}/H$ but not in Case $5/\mathrm{B}/\bar{\mathrm{H}}$. Therefore, if (1), (2), (3), and (4) are sufficiently large, whereas (5) is relatively small, *society* would prefer Case $5/\mathrm{B}/\bar{\mathrm{H}}$ to Case $2/\bar{\mathrm{C}}/\mathrm{H}$. By contrast, as in the example of a solution, under some circumstances, decentralized decision-making by *factory* and *utility* (e.g., Case 2/$\bar{\mathrm{C}}$/H is optimal to Game I) would not lead to the optimal outcome from the perspective of *society* (e.g., *society* might prefer Case $4/C/H$ or Case $5/\mathrm{B}/\bar{\mathrm{H}}$).

To achieve the social optima, the government has to either 1) encourage *utility* to harden the grid when *factory* purchases a CHP (Case $4/C/H$ in Figure 1), or 2) encourage *factory* to purchase a CHP with blackstart capability and *utility* not to harden the grid (Case $5/B/\bar{H}$ in Figure 1). In those two cases, *society* harnesses both the benefits of resiliency and energy efficiency (and thus emission reductions). Note that with Influence 1, *factory* will voluntarily invest in CHP because its payoff (cost) in Case $4/C/H$ is better than that in Case $2/\bar{C}/H$ based on assumption 1. By contrast, if Influence 2 does not require *factory* to invest in a CHP with blackstart capability, *factory* will not do so, as its payoff (cost) in Case $2/\bar{C}/H$ is better than that in Case $5/B/\bar{H}$ (see Appendix A.1).

3.5.2 Game II and its solution

Then, we examine the case where the order of decision making between *factory* and *utility* is reversed (they play Game II instead and *utility* decides first). With the same set of conditions, Case $5/B/\bar{H}$ (i.e., *factory* invests in a CHP with blackstart capability and *utility* does not harden the grid) is the decentralized optimal solution to Game II in Figure 1. Note that under the above set of conditions, investing in a CHP with blackstart capability could be optimal for *factory* only if *utility* moves first (and chooses not to harden the grid after analyzing the best response of *factory*), or if there is some regulation influencing *factory* to invest in a CHP with blackstart capability and *utility* not to harden the grid. Therefore, if *factory* and *utility* make independent decisions without governance, social optima might not be achieved. A potential remedy is for the government to either influence the decisions about *utility* and private investments on resiliency, or to choose a particular order of decision making

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for the sequential game between *factory* and *utility*. The detailed solution process is as follows:

<u>Step 1</u>: we solve Subgame 1 by comparing *factory* payoffs for Cases $1/\bar{C}/\bar{H}$, $3/C/\bar{H}$ and $5/B/\bar{H}$. The difference (Case $1/\bar{C}/\bar{H}$ subtracting Case $5/B/\bar{H}$) is $T_b^{15} - b$. Similarly, the difference (Case $3/C/\bar{H}$ subtracting Case $5/B/\bar{H}$) is $T_b^{35} - b$. Therefore, if $b < \min\{T_b^{15}, T_b^{35}\}$, Case $5/B/\bar{H}$ solves Subgame 1. <u>Step 2</u>: we solve Subgame 2 by comparing *factory* payoffs for Cases $2/\bar{C}/H$, $4/C/H$, and $6/B/H$. The difference (Case $2/\bar{C}/H$ subtracting Case $4/C/H$) is $T_c^{24} - c$. Similarly, the difference (Case $4/C/H$ subtracting Case $6/B/H$) is $T_b^{46} - b$. In short, if $c < T_c^{24}$, and $b > T_b^{46}$, Case $4/C/H$ solves Subgame 2. <u>Step 3</u>: we solve the whole game by comparing *utility* payoffs for Cases $4/C/H$ and $5/B/\bar{H}$. The difference (Case $5/B/\bar{H}$ subtracting Case $4/C/H$) is $T_K^{54} - K$. Therefore, if $K > T_K^{54} = T_K^{34}$, Case $5/B/\bar{H}$ is optimal. Note that *utility*'s payoff of Case $3/C/\bar{H}$ ($4/C/H$) equals that of Case $5/B/\bar{H}$ ($6/B/H$). In sum, if $T_K^{34} < K$, $c < T_c^{24}$, and $T_b^{46} < b < min\{T_b^{15}, T_b^{35}\}$, Case $5/B/\bar{H}$ is optimal to Game II.

After combining the constraints defining the decentralized optima to Games I and II, we have Case $2/\bar{C}/H$ to be optimal to Game I, whereas Case $5/B/\bar{H}$ is optimal to Game II under the common conditions that $T_K^{34} < K < T_K^{12}$, $T_c^{23} < c < T_c^{24}$, and $\max\{T_b^{46}, T_b^{25}\} < b < \min\{T_b^{15}, T_b^{35}\}$. Note that if $c > T_c^{23} > T_c^{24}$, Case $2/\bar{C}/H$ is still optimal to Game I, the decentralized optimum changes for Game II. In particular, in <u>Step 2</u>, since $T_c^{24} < c$, Case $2/\bar{C}/H$ solves Subgame 2 (Case $2/\bar{C}/H$ is preferred to Case $4/C/H$, which is in turn preferred to Case $6/B/H$). Then, in <u>Step 3</u>, since $T_b^{25} < b$, Case $2/\bar{C}/H$ is preferred to Case $5/B/\bar{H}$ and solves Game II. Therefore, if $T_c^{23} > T_c^{24}$ (one of the requirements for the existence of the two equilibrium solutions fails), Case $2/\bar{C}/H$ solves both Games I and II.

The above is one example of some additional requirements besides the five assumptions that must hold for the above two equilibrium solutions to exist because upper thresholds must be greater than their corresponding lower thresholds. Listed below are those requirements, along with their mathematical expressions.

1. Benefit of hardening the grid is greater to *utility* without CHP than with CHP due to assumptions 1 and 4 ($T_K^{34} < T_K^{12}$)
2. Benefit of hardening the grid is greater to *factory* than its cost, given *factory* invests in a CHP ($T_c^{23} < T_c^{24}$)

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3. Benefit of hardening the grid is greater to *factory* than its cost, given *factory* does not invest in a CHP ($T_b^{25} < T_b^{15}$)
4. Net benefit of a CHP is less to *factory* than net benefit of hardening the grid ($T_b^{25} < T_b^{35}$)
5. Benefit of a CHP with blackstart capability is greater than the sum of cost of CHP (minus incentive) and additional benefit of blackstart capability, given *factory* invests in a CHP ($T_b^{46} < T_b^{15}$)
6. Benefit of blackstart capability is greater to *factory* without hardened grid than with hardened grid, given *factory* invests in a CHP ($T_b^{46} < T_b^{35}$)

For requirement 2., by definition, $T_c^{23} = (\text{Factory Payoff in Case 2} - \text{Factory Payoff in Case 4}) + c$; and $T_c^{24} =$ (Factory Payoff in Case 2 – Factory Payoff in Case 4) $+ c$. Therefore, $T_c^{23} - T_c^{24} =$ (Factory Payoff in Case 4 − Factory Payoff in Case 3) = (Factory Payoff when Utility Hardens the Grid and Factory Purchases CHP − Factory Payoff when Utility Does not Harden the Grid and Factory Purchases CHP) = (Cost of Hardening the Grid to Factory (c_H) – Benefit of Hardening the Grid to Factory when Factory Purchases CHP). That is why $T_c^{23} < T_c^{24}$ implies that the benefit of hardening the grid is greater to *factory* than its cost given that factory invests in a CHP. That is how c_H is related to the thresholds. Similarly, for requirement 3., $T_b^{25} =$ (Factory Payoff in Case 2 – Factory Payoff in Case 5) $+ b$; and $T_b^{15} =$ (Factory Payoff in Case 1 – Factory Payoff in Case 5) $+ b$. Therefore, $T_c^{25} - T_c^{15} =$ (Factory Payoff in Case 2 − Factory Payoff in Case 1) = (Factory Payoff when Utility Hardens the Grid – Factory Payoff when Utility Does not Harden the Grid) = (Cost to Factory (c_H) − Benefit of Hardening the Grid to Factory). That is why $T_c^{25} < T_c^{15}$ implies that the benefit of hardening the grid is greater to *factory* than its cost given that *factory* does not invest in a CHP. For requirement 4., $T_b^{25} =$ (Factory Payoff in Case 2 − Factory Payoff in Case 5) $+b$; and $T_b^{35} =$ (Factory Payoff in Case 3 – Factory Payoff in Case 5) $+b$. Therefore, $T_b^{25} - T_b^{35} =$ (Factory Payoff in Case 2 – Factory Payoff in Case 3) = (Factory Payoff when Utility Hardens the Grid – Factory Payoff when Utility Does not Harden the Grid and Factory Purchase CHP) = (Hardening Cost to Factory (c_H) + Energy Cost with Hardened Grid + Outage Cost with Hardened Grid − (Cost to Factory of Purchasing CHP – CHP incentive + Energy Cost with CHP + Outage Cost with Unhardened Grid)) = (Hardening Cost to Factory (c_H) + Energy Cost with Hardened Grid + Outage Cost with Hardened Grid − (Cost to Factory of Purchasing CHP – CHP incentive + Energy Cost

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with CHP + Outage Cost with Unhardened Grid) + (Energy Cost with Unhardened Grid and without CHP + Outage Cost with Unhardened Grid) − (Energy Cost with Unhardened Grid and without CHP + Outage Cost with Unhardened Grid)) = (Hardening Cost to Factory (c_H) − Benefit of Hardening the Grid – (Cost to Factory of Purchasing CHP – CHP incentive – Benefit of CHP)) = (Net Benefit of CHP – Net Benefit of Hardening the Grid). That is why $T_d^{25} < T_d^{35}$ implies that net benefit of a CHP is less to *factory* than net benefit of hardening the grid. For requirement 5., T_b^{46} = (Factory Payoff in Case 4 –Factory Payoff in Case 6) + b = (Cost of CHP – CHP incentive + Cost of Hardening the Grid + Energy Cost with Hardened Grid and CHP + Outage Cost with Hardened Grid – (Cost of CHP with Blackstart Capability (b)– CHP incentive + Cost of Hardening the Grid + Energy Cost with Hardened Grid and CHP + CHP Operation Cost During Outages)) +b = (Cost of CHP + Outage Cost with Hardened Grid – CHP Operation Cost During Outages) = (Cost of CHP + Additional Benefit of Blackstart Capability); and T_b^{15} = (Factory Payoff in Case 1 – Factory Payoff in Case 5) + b = (Energy Cost without Hardened Grid and CHP + Outage Cost without Hardened Grid and CHP – (Cost of CHP with Blackstart Capability (b) – CHP incentive + Energy Cost with Unhardened Grid and CHP + CHP Operation Cost During Outages) + b = Benefit of CHP with Blackstart Capability + CHP incentive. Therefore, $T_b^{46} - T_b^{15}$ = (Cost of CHP + Additional Benefit of Blackstart Capability − Benefit of CHP with Blackstart Capability– CHP incentive). That is why $T_b^{46} < T_b^{15}$ implies that the benefit of CHP with blackstart capability is greater than the sum of the cost of CHP (minus incentive) and the additional benefit of blackstart capability during outages given *factory* invests in a CHP.

3.6 Example of a solution for the simultaneous game

If $T_K^{34} < K < T_K^{12}$, $T_c^{24} < T_c^{23} < c$, and $\max\{T_b^{46}, T_b^{25}\} < b < \min\{T_b^{15}, T_b^{35}\}$ or the costs for grid hardening (K) and a CHP with blackstart capability (b) are modest, whereas cost of a CHP (c) is high, the decentralized optimal solution to the two sequential games (Case $2/\bar{C}/H$) also solves the simultaneous game in Section 3.3. This is because both players' equilibrium strategies are best responses to the other player's equilibrium strategy. By contrast, if $T_K^{34} < K < T_K^{12}$, $T_c^{23} < c < T_c^{24}$, and $\max\{T_b^{46}, T_b^{25}\} < b < \min\{T_b^{15}, T_b^{35}\}$, the best response of *utility* to *factory*'s strategy of $\bar{C}$ is H, to C and to B is $\bar{H}$ whereas the best response of *factory* to *utility*'s strategy of $\bar{H}$ is B and to H is C. Therefore, Case $5/B/\bar{H}$ is the pure strategy equilibrium to the simultaneous game, which is the same as in Game I where *factory* moves first, but different from Game II where *utility* moves first. One policy implication is that if Case $5/B/\bar{H}$ is socially desirable, government might either let *factory* move first or encourage *factory* and *utility* to decide without knowing the other's decision, which might not be practical due to reasons stated in Section 3.1. By contrast, determining order of decision making might make it much easier for the government to achieve the same outcome, at least in this example.

3.7 Analytical sensitivity analyses

Section 3.5 presents an example of a solution when the order of moves matters in sequential games. In this section, we conduct sensitivity analyses to show analytically how the decentralized optimal solution changes as key parameters change. Figure 2 shows the results where the cost of grid hardening is (a) large, (b) small, (c) relatively large, (d) relatively small, and (e) medium. On Figure 2, the thresholds for the 5 cases with different costs of grid hardening are selected based on the equilibrium solutions for solving Game I and Game II.

The order of $T_K^{14} < T_K^{34} < T_K^{12} < T_K^{32}$ is derived from the assumptions and requirements for the equilibrium solution to exist. In particular, $T_K^{14} - T_K^{34} =$ (Utility Payoff in Case 1 – Utility Payoff in Case 4 + K – (Utility Payoff in Case 3 – Utility Payoff in Case 4 + K))= (Utility Payoff in Case 1 – Utility Payoff in Case 3)= ($-$ Electricity Sales without CHP + Electricity Sales with CHP) $= -\sum_{t=1}^{20}\left(\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}\right)(e+e^W)(1-d)^t + \sum_{t=1}^{20}\left(\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}\right)(e_c+e^W)(1-d)^t < 0$ since cost of annual electricity consumption of *factory* is assumed to be lower with a CHP than without a CHP (assumption 3: $e > e_c$). Similarly, $T_K^{12} - T_K^{32} =$ (Utility Payoff in Case 1 – Utility Payoff in Case 2 + K – (Utility Payoff in Case 3 – Utility Payoff in Case 2 + K))= (Utility Payoff in Case 1 – Utility Payoff in Case 3)= ($-$Electricity Sales without CHP + Electricity Sales with CHP) $= -\sum_{t=1}^{20}\left(\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}\right)(e+e^W)(1-d)^t + \sum_{t=1}^{20}\left(\frac{\sum_l p_N^l(M-l)+(1-\sum_l p_N^l)M}{M}\right)(e_c+e^W)(1-d)^t < 0$ since cost of annual electricity consumption of *factory* is assumed to be lower with a CHP than without a CHP (assumption 3: $e > e_c$). Moreover, $T_K^{34} - T_K^{12} < 0$ is from the first requirement for the equilibrium solution to exist (i.e., $T_K^{34} < T_K^{12}$). For Figure 2(a), if $K \geq T_K^{32}$, the value of K is also greater than all of the other thresholds. That is why $K \geq T_K^{32}$ implies that the cost of hardening the grid is large. Similarly, for Figure 2(b), if $K < T_K^{14}$, the value of K is also smaller than all of the other thresholds.

That is why $K < T_K^{14}$ implies that the cost of hardening the grid is small. For Figure 2(c), $T_K^{12} < K < T_K^{32}$ implies that the value of K is also larger than T_K^{14} and T_K^{34} and thus relatively large. For Figure 2(d), $T_K^{14} < K < T_K^{34}$ implies that the value of K is also smaller than T_K^{12} and T_K^{32} and thus relatively small. Finally, for Figure 2(e), $T_K^{14} < T_K^{34} < K < T_K^{12} < T_K^{32}$ implies that the value of K is in the middle of the four thresholds and thus medium.

While social desirability depends on problem parameters, we can reasonably expect Cases $4/C/H$ and $5/B/\bar{H}$ to be preferred by *society* where *society* obtains both reliability and environmental benefits (see some of the arguments in Section 3.5.1). By contrast, Case $1/\bar{C}/\bar{H}$ is likely to be socially undesirable due to unreliable electric distribution system and energy inefficiency. The following discussion is based on these reasonable expectations.

First, from Figures 2(a) and 2(b), we find that the order does not matter when the cost of grid hardening (K) is large (a) or small (b). For example, in Figure 2(a), if capital cost of CHP with blackstart capability is small (i.e., $b < \min(T_b^{35}, T_b^{15})$), Case $5/B/\bar{H}$, where *factory* invests in a CHP with blackstart capability and *utility* does not harden the grid, is optimal to both Games I and II. Moreover, if K is large, Not Harden is the dominant strategy for *utility* (Figure 2(a)); whereas if K is small, Harden is the dominant strategy for *utility* (Figure 2(b)).

From Figure 2(a), Case $5/B/\bar{H}$ could be preferred by *society* over Case $3/C/\bar{H}$ (e.g., when VOLL for *factory* is large). However, government cannot induce Case $5/B/\bar{H}$ over Case $3/C/\bar{H}$ by another policy instrument, which is the subsidy for a CHP investment. Government may reduce the area where a potential socially undesirable outcome (Case $1/\bar{C}/\bar{H}$) is reached by reducing the capital costs of CHP and CHP with blackstart capability (note that the social desirability depends on particular benefit/cost parameters, and Case $1/\bar{C}/\bar{H}$ appears socially undesirable as seen in the numerical example in Section 4). The incentive for a CHP investment does not affect the conditions (if $b > T_b^{35}$, Case $3/C/\bar{H}$ is optimal; if $b < T_b^{35}$, Case $5/B/\bar{H}$ is optimal) distinguishing those two cases. The same argument applies to the distinction between Cases $4/C/H$ and $6/B/H$ in Figure 2(b). One suggestion might be to subsidize CHP with blackstart capability more than CHP. However, this also depends on K. If K is large (Figure 2(a)), doing so encourages Case $5/B/\bar{H}$ over Case $3/C/\bar{H}$. However, if K is small (Figure 2(b)), the result becomes Case $6/B/H$ over Case $4/C/H$, which might result in investment redundancy, a potentially socially undesirable outcome. In sum, government could implement a differential subsidy policy based on the cost of grid hardening to reach a social optimum. Alternatively, government could simply subsidize either CHP or CHP with blackstart capability but also subsidize grid hardening. The choice between those two alternatives would depend on the total governmental expenditure.

Second, from Figures 2(c) and 2(d), we observe similar results as in Figures 2(a) and 2(b), except in areas where $T_K^{12} < K < T_K^{32}, T_c^{24} < c < T_c^{13}, b > T_b^{26}$ and $T_K^{14} < K < T_K^{34}, c > T_c^{13}, T_b^{15} < b < T_b^{26}$. In these areas, the order matters. For instance, if $T_K^{12} < K < T_K^{32}, T_c^{24} < c < T_c^{13}, b > T_b^{26}$, Case $3/C/\bar{H}$ is optimal to Game I whereas Case $2/\bar{C}/H$ is optimal to Game II. Therefore, depending on *society*'s payoffs in Cases $3/C/\bar{H}$ and $2/\bar{C}/H$, government would have a preferred order for the sequential game between *factory* and *utility*. In particular, if *society* values a resiliency benefit to the public (as in Case $2/\bar{C}/H$) more than energy efficiency (as in Case $3/C/\bar{H}$), government would prefer *utility* to move first (Game II). By contrast, if *society* values the resiliency benefit to the public (as in Case $2/\bar{C}/H$) less than energy efficiency (as in Case $3/C/\bar{H}$), government would prefer *factory* to move first (Game I). Similarly, if $T_K^{14} < K < T_K^{34}, c > T_c^{13}, T_b^{15} < b < T_b^{26}$, Case $6/B/H$ is optimal to Game I whereas Case $1/\bar{C}/\bar{H}$ is optimal to Game II. Unless the costs for a CHP with blackstart capability and grid hardening are prohibitive, government would prefer *factory* to move first (Game I).

Finally, in Figure 2(e), there are more areas where the order matters when the cost of grid hardening is medium ($T_K^{14} < T_K^{34} < K < T_K^{12} < T_K^{32}$). If parameter settings are such that the situation is in one of these areas, government would prefer one of the two games to facilitate a more socially desirable outcome. Interestingly, comparison between the area where $T_c^{23} < c < T_c^{13}, T_b^{35} < b < T_b^{26}$ and the area where $T_c^{24} < c < T_c^{23},\ b > T_b^{26}$ reveals that the decentralized optimal solutions to Games I and II are reversed in the two areas. For example, the decentralized optimum to Game I is Case $2/\bar{C}/H$ in the area where $T_c^{23} < c < T_c^{13}, T_b^{35} < b < T_b^{26}$, while it is the decentralized optimum to Game II in the area where $\mathrm{T_c^{24} < c < T_c^{23}, b > T_b^{26}}$. Therefore, for a particular government intervention procedure (e.g., regulating the order for the sequential game between *factory* and *utility*), success will depend on the parameter settings.

By comparing across Figures 2 (a)-(e), Case $1/\bar{C}/\bar{H}$ could never be reached when the cost of grid hardening is at the low level (Figures 2(b) versus Figures 2(a)). One potential policy instrument for government is to subsidize grid hardening if its cost is high and a socially undesirable outcome would be reached. Note that the detailed solution process is omitted due to space limitations but is available upon request.

4. Numerical example

While analytical solutions yield insights, we illustrate our model with typical data to determine what might happen in practice. The estimates are partly based on historical records for parameters as listed in Table 1, and readers are referred to Athawale and Felder (2014) for detailed descriptions of how those estimates were obtained. Note that we assume that *factory* invests in a gas-turbine CHP and compute the ratio of expected hours of annual energy consumption (or *factory* operating) given there is some probability of outages to maximum hours of annual energy consumption by *factory*, and use this ratio to represent the probability that *factory* operates normally during a given year. In addition, for simplicity, we assume *utility* pays the full cost of grid hardening (i.e., $F = 0$; empirical sensitivity analysis relaxes this assumption). Gas consumption during outages is negligible since the length of outage per year is short compared to the number of hours in a year (i.e., 4/8,760=0.0005), and that there is only one outage per year of length 4 hours. Outage duration of 4 hours is chosen since average U.S. outage length experienced annually is 3 hours (Campbell, 2012) and VOLLs of 4-hour outages are readily available (Sullivan et al., 2009). Because *factory*'s annual electricity consumption is 1.21×10^7 kWh (=$\$\,1.57 \times 10^6$ per kWh/\$0.13; i.e., cost of electricity divided by electric tariff), it is classified as a large commercial/industrial customer (electric consumption > 50,000 kWh per year) and \$18.20 is its VOLL (per unserved kWh) of a 4-hour outage (Sullivan et al., 2009). On the other hand, the other customer represents a group of residential, commercial, and industrial customers (or any mix thereof); and we use \$40.20 (per unserved kWh) as its VOLL, which is a weighted mean of VOLL for a residential customer (\$1.3 per unserved kWh) experiencing a 4-hour outage that for a small commercial/industrial customer (\$373.1 per unserved kWh) experiencing a 4-hour outage, and that for a large commercial/industrial customer (\$18.20 per unserved kWh) experiencing a 4-hour outage (Sullivan et al., 2009). The weights were chosen based on a utility's (PSE&G) customer mix. That is, in 2012, 86.88% PSE&G customers are residential, 12.69% are commercial, and 0.43% are industrial. Note that we assume that PSE&G commercial customers are small commercial/industrial customers, and its industrial customers are large commercial/industrial customers according to the classification in Sullivan et al. (2009).

Table 3 lists the payoffs for the three parties for this example. We find that if *factory* invests in a gas-turbine CHP, the decentralized optimum specifies that *factory* invests in a CHP with blackstart capability and *utility* does nothing (Case $5/B/\overline{H}$), regardless of the order of moves. Please refer to Figure 1 for identification of subgames and also the solution process for the definition of the steps. In Step 1, first, we solve Subgame I by comparing *utility* payoffs for Case $1/\overline{C}/\overline{H}$ and Case $2/\overline{C}/H$. Since -200.05 (Case $2/\overline{C}/H$)> -200.98 (Case $1/\overline{C}/\overline{H}$), Case $1/\overline{C}/\overline{H}$ solves Subgame I (the case with the lower cost is preferred). Similarly, Case $3/C/\overline{H}$ solves Subgame II (-194.19 > -195.23). Case $5/B/\overline{H}$ solves Subgame III (-194.19 > -195.23). In Step 2, we solve Game I by comparing *factory* payoffs for Case $1/\overline{C}/\overline{H}$, Case $3/C/\overline{H}$, and Case $5/B/\overline{H}$. Since 23.97 (Case $5/B/\overline{H}$) < 25.18 (Case $3/C/\overline{H}$) < 27.26 (Cases $1/\overline{C}/\overline{H}$), Case $5/B/\overline{H}$ solves Game I (when *factory* moves first) and is its decentralized optimum. Additionally, the optimal outcome for *society* is Case $6/C/H$, which cannot be achieved by determining the order of moves.

4.1 Empirical sensitivity analyses

We also conduct sensitivity analyses with regard to two key parameters: the cost of grid hardening (K), and the outage cost for *factory*. First, we find that if K decreases from \$1 million to below \$0.07 million, the decentralized optimum to both games becomes Case $6/B/H$. Note that K or how much grid hardening costs *utility* could be influenced by government's decision, either through direct subsidy or rate case approval. This suggests that if government provides an incentive of more than \$0.93 million to *utility* for grid hardening, Case $6/B/H$ can be reached instead of Case $5/B/\overline{H}$, with an improvement of \$24.92 million (\$53.73 million − \$28.81 million) for *society*. In this particular case, we see that subsidizing grid hardening to achieve a socially more desirable outcome is cost-beneficial. Therefore, Case $6/B/H$ does appear to be a win-win situation for all parties in the game of resiliency/reliability improvement initiative, while Case $5/B/\overline{H}$ would be reached without government intervention. Second, given that K is \$0.07 million, if the outage cost for *factory* decreases to below \$0.12 million from \$0.17 million (29.4% decrease), the decentralized optimal solution becomes Case $4/C/H$, which is also the social optimum (that changes with parameters).

Moreover, we conducted Monte Carlo simulations to explore the uncertainties/variability (in CHP technology) in key parameter estimates by randomly drawing them from uniform distributions except for the capacity factor, which is from a normal distribution with a mean of 62% and a standard deviation of 10% (Athawale and Felder,

2014) and an outage length, which is drawn from a discrete set of 5 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours and their corresponding VOLLs. In particular, we let probability of outage given a hardened grid (p_H^l) be between 0 and 0.2, probability of outage given an unhardened grid (p_N^l) be between 0.7 and 0.9, cost of grid hardening to *utility* (K) and *factory* (c_H) be between \$0 and \$2 million, and \$0 and \$0.2 million, respectively, cost of annual electric consumption (e^W) for the other customer be between \$0 and \$31.40 million and its hourly demand (D^W) be between \$0 and \$24,000, VOLL of the other customer (V^W, per unserved kWh) be between \$21.60 and \$2,401 (a 5-minute outage), between \$4.40 and \$556.30 (a 30-minute outage), between \$2.60 and \$373.10 (a 1-hour outage), between \$1.30 and \$307.30 (a 4-hour outage), and between \$0.90 and \$271.70 (a 8-hour outage). We set the lower bound of V^W to be the VOLL of a residential customer and its upper bound to be that of a small commercial/industrial customer (Sullivan et al., 2009).

One potential policy instrument of government is to control the incentive given for CHP investments. Therefore, we consider seven levels of incentive (from 0% to 30% in steps of 5% of the capital cost of the CHP). We observe that only 30% of the capital cost of CHP as incentive leads to a lower frequency of occurrence of Cases $1/\bar{C}/\bar{H}$ and $2/\bar{C}/H$ with little effect on the other four cases. Figure 1 shows the frequencies of six outcomes as optimal to the sequential games in Figure 1 from Monte Carlo simulations where 30% of the capital cost of CHP is covered by incentive.

First, we find that Case $1/\bar{C}/\bar{H}$ occurs most often (65% in Game I and 66% in Game II), suggesting that costs of grid hardening and CHP are still high even after government's incentive. Cases $3/C/\bar{H}$ and $5/B/\bar{H}$ occur with second and third most frequencies due to government's incentive. However, both cases could be socially undesirable because of unhardened grid. Case $5/B/\bar{H}$ is more likely to occur when *factory* moves first (13%) than when *utility* moves first (5%). By contrast, Case $2/\bar{C}/H$ is much more likely to occur when *utility* moves first (8%) than when *factory* moves first (1%). Case $2/\bar{C}/H$ is socially desirable in the numerical illustration because emission reductions achieved by CHP and energy cost saving do not outweigh its cost. However, as social cost of carbon increases, Case $2/\bar{C}/H$ might be less socially desirable than Cases $4/C/H$ and $6/B/H$. Second, Cases $4/C/H$ and $6/B/H$ which are socially most undesirable in the numerical illustration, are not likely to occur regardless of order of moves (<1%). In general, the government might prefer *utility* to move first to achieve Case $2/\bar{C}/H$. Because the uncertainty ranges and the number of uncertain key parameters are large, for particular projects, the government might invest in narrowing uncertainty ranges of benefits/costs of resiliency measures and use regulatory power to facilitate the achievement of socially desirable outcomes.

5. Conclusion and future research directions

In this paper, we developed a game-theoretical modeling framework to investigate the strategic interactions between two important players in the electricity market, namely, *utility* (electricity deliverer) and *factory* (a main electricity consumer). We assume that the games are non-cooperative and occur with complete and perfect information. First, we studied the sequential game where *factory* makes the first decision of whether to invest in a CHP with or without blackstart capability and then *utility* decides whether or not to harden its electricity distribution network. We found that when the costs of both grid hardening and a CHP without and with blackstart capability are medium, the decentralized optimal solution is that *factory* does not invest in a CHP and *utility* hardens its electricity distribution network. Moreover, the decentralized optimal outcome might not be optimal for *society*/government, which could select an order of moves for the sequential game and incentivize investments in CHPs with and without blackstart capability as well as grid hardening.

We also investigated the role of government, which either encourages *utility* to harden its electricity distribution network given that *factory* invests in CHP, or encourages *factory* to invest in a CHP with blackstart capability and *utility* not to harden the grid. With the first influence, we found that under the same set of conditions as above, the decentralized optimal solution changes. That is, at optimality, *factory* invests in a CHP and *utility* hardens its electricity distribution network. We conclude that due to their profit maximizing nature, *factory* and *utility* could not achieve the social optimum (e.g., *factory* invests in a CHP and *utility* hardens its electricity distribution network) if *factory* moves first without regulatory governance.

Furthermore, we studied the game where *utility* decides first and *factory* follows (without regulatory governance) and a simultaneous game, where they decide without knowing the other's decision. We found that under the same conditions as above, at optimality, *utility* does not harden the electricity distribution system and *factory* invests in a CHP with blackstart capability. We conclude that given that *utility* decides first, or the two decision-makers decide simultaneously, the decentralized solution could be optimal for all three parties even without regulatory governance. A policy implication is that to achieve the socially desired outcome, the social planner could allow *utility* to make its own decision of whether to harden the electricity distribution system and publicize *utility*'s decision. Simultaneous games are much more difficult to achieve in practice. Alternatively, the social planner could recommend *factory* to delay the decision of investing in a CHP until *utility* makes a decision about hardening its electricity distribution systems. Note that the above recommendation assumes the conditions that capital costs of both grid hardening and a CHP with or without blackstart capability are medium.

We also conducted analytical sensitivity analysis to study how the decentralized optimal solution to the sequential games changes following small variations in some of the key parameters and found that when the cost of grid hardening is large or small, the order of moves will not affect the decentralized optimum and there is no need for regulatory governance. However, when the cost of grid hardening is medium, the order of moves could make a difference under additional conditions. If the parameter setting leads to a socially undesirable outcome, government might be able to incentivize investments on grid hardening and/or CHP with or without blackstart capability to avoid such a negative outcome. Furthermore, if the order of moves matters after those incentives, government could employ its regulatory power by selecting an order for the sequential game between *factory* and *utility*.

We illustrated our modeling framework with some typical and realistic data to investigate what outcomes might arise without governance. We showed that if the *factory* invests in a gas-turbine CHP and runs the CHP during a significant portion of any given year, the decentralized optimal solution is that *factory* invests in a CHP with blackstart capability and *utility* does not harden the grid regardless of the order of moves. Empirical sensitivity analyses show that if the CHP is run for a significantly long period of time per year and the cost of grid hardening is sufficiently low, the case, where *factory* invests in a CHP with blackstart capability and *utility* hardens the grid, becomes optimal regardless of the order of moves. However, if VOLL for *factory* is sufficiently small, the optimal solution becomes the case where *factory* invests in a CHP and *utility* hardens the grid. Therefore, if government incentivizes grid hardening, which is cost-beneficial, a win-win situation for all three parties can arise.

Finally, we conducted Monte Carlo simulations to account for uncertainty/variability in key parameters. We found that without governance, the case where both *factory* and *utility* do nothing occurs most often, which is most socially undesirable. The case where *factory* does nothing and *utility* hardens the grid happens more frequently when *utility* moves first than when *factory* moves first. We conclude that for a particular project, it might be in the government's interest to narrow the uncertainty ranges of key cost/benefit parameters to arrive at insightful regulations and/or policies.

We identified several interesting future research directions. First, extending the game to a three-stage game where *factory* (which did not invest in CHP in Stage 1 can choose one of three options: 1) do nothing, 2) invest in CHP, and 3) invest in CHP with blackstart capabilities after a number of years when the decision of *utility* is already public. Second, we could also study the case where the capacity factor of CHP is uncertain (how long a CHP will operate once it is implemented) and explore the optimal strategies of both *factory* and *utility*. Third, we could investigate the effects of different CHP technologies upon the sequential game between *factory* and *utility*. Finally, we could investigate different distributions and ranges for Monte Carlo simulations and characterize effects of different parameters on the solution.

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Table 1: Problem parameters, decision variables, outcomes, and notation

Notation and Estimate	Description
Problem Parameters	
$l = 4$	Outage length (hours)
$p_H^l = 0.1$	Probability of an l-hour outage in a year given the grid is hardened (%)
$p_N^l = 0.8$	Probability of an l-hour outage in a year given the grid is not hardened (%)
$K = 1$	Cost of grid hardening ($ millions) to *utility*
$F = 0$	Portion of the capital cost of grid hardening to *utility* for return over time
$c_H = 0.1$	*Factory*'s contribution to cover the cost of grid hardening ($ millions)
$V(l) = 18.20$ $V^W(l) = 40.20$	Value of Lost Load (VOLL) from an l-hour outage for *factory* and the other customer ($ per unserved kWh), respectively
$h_O = 5{,}431$	Hours of CHP operation in a year (hours) implying that the Capacity Factor equals 62%
$e^W = 15.7$[a]	Cost of annual electricity consumption ($ millions) for the other customer
$i = 0.59$	Incentive given to *factory* for purchasing and installing a CHP ($ millions) regardless of blackstart capability
t	Time period (years), from 0 to 20 years
$c = 3.82$	Cost of purchasing a CHP ($ millions)
$b = 3.95$	Cost of purchasing a CHP with black-start capability ($ millions)
$c_O(h_O) = 0.06$[a]	Annual operation and maintenance cost of a CHP ($ millions)
$S(h_O, D) = 0.16$[a]	Annual standby charge ($ millions)
$e = 1.57$[a]	*Factory*'s cost of purchasing electricity from *utility* ($ millions)
$e_c = 0.83$[a]	*Factory*'s cost of purchasing electricity from *utility*, when CHP is installed
$g = 0.62$ [a]	*Factory*'s cost of annual gas consumption ($ millions)
$g_c = 0.93$ [a]	*Factory*'s cost of annual gas consumption with a CHP ($ millions)
$g_c^b(l) = 0$	*Factory*'s cost of gas consumption running a CHP in island mode ($ millions)
$k = 1{,}070$	CHP electric capacity (kW)
$D = 2{,}300,$	*Factory*'s and the other customer's average hourly electricity demands (kW), respectively
$d = 8$	Discount rate (% per year)
$M = 8{,}760$	Hours in a year (hours)
$f = 0.13$	Electric tariff ($/kWh)
$u = 39.77$[a]	Social cost of carbon ($/ton)
$n(h_o) = 4{,}723{,}419$	Avoided CO_2 emission by generators on the grid displaced by CHP (ton)
$r^o = 3.20$	Cost escalation for operations and maintenance of a CHP (% per year)
$r^e = 1.98$	Electric tariff escalation (% per year)
$r^g = 3.20$	Gas tariff escalation (% per year)
$\alpha,\ \beta = 1, \ldots, 6$	Game outcome (Case) identity
Decision Variables	
No CHP	*Factory*'s decision of not investing in a CHP
CHP	*Factory*'s decision of investing in a CHP
CHP+B/S	*Factory*'s decision of investing in a CHP with blackstart capability
Not Harden	*Utility*'s decision of not hardening the electric power grid
Harden	*Utility*'s decision of hardening the electric power grid
Game Outcomes	
Case $1/\bar{C}/\bar{H}$	Case 1 in Figure 1, where *factory* chooses No CHP and *utility* chooses Not Harden
Case $2/\bar{C}/H$	Case 2 in Figure 1, where *factory* chooses No CHP and *utility* chooses Harden
Case $3/C/\bar{H}$	Case 3 in Figure 1, where *factory* chooses CHP and *utility* chooses Not Harden
Case $4/C/H$	Case 4 in Figure 1, where *factory* chooses CHP and *utility* chooses Harden
Case $5/B/\bar{H}$	Case 5 in Figure 1, where *factory* chooses CHP+B/S and *utility* chooses Not Harden
Case $6/B/H$	Case 6 in Figure 1, where *factory* chooses CHP+B/S and *utility* chooses Harden
Thresholds for Equilibrium Conditions	
$T_K^{\alpha\beta}$	*Utility*'s payoff in Case α minus *utility*'s payoff in Case β plus K
$T_c^{\alpha\beta}$	*Utility*'s payoff in Case α minus *utility*'s payoff in Case β plus c
$T_b^{\alpha\beta}$	*Factory*'s payoff in Cases α minus *factory*'s payoff in Case β plus b

[a] Adjusted for discounting and escalation over the years in the illustration

Table 2: *Factory*, *utility* and *society* payoffs of six cases in Figure 1.

Case	***Factory* Payoff (Cost)**	***Utility* Payoff (Cost − Revenue)**	***Society* Payoff (Cost)**
1 $\bar{C}, \bar{H}$	$\sum_t \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e + g)(1-d)^t + \sum_t \sum_l p_N^l l D(V(l) - f)(1-d)^t$	$-\sum_t \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e + e^W)(1-d)^t$	$\sum_t \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e + g)(1-d)^t + \sum_t \sum_l p_N^l l[D(V(l) - f) + D^W(V^W(l) - f)](1-d)^t$
2 $\bar{C}, H$	$c_H + \sum_t \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e + g)(1-d)^t + \sum_t \sum_l p_H^l l D(V(l) - f)(1-d)^t$	$K - \sum_t FK(1-d)^t - \sum_t \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e + e^W)(1-d)^t$	$K - \sum_t FK(1-d)^t + c_H + \sum_t \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e + g)(1-d)^t + \sum_t \sum_l p_H^l l[D(V(l) - f) + D^W(V^W(l) - f)](1 - d)^t$
3 $C, \bar{H}$	$c - i + \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e+g) + \sum_{t=1}^{20} \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)\left(e_c + g_c + S\left(h_o, D\right) + c_o(h_o)\right)(1-d)^t + \sum_t \sum_l p_N^l l D(V(l) - f)(1-d)^t$	$-\left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e + e^W) - \sum_{t=1}^{20} \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e_c + e^W)(1-d)^t$	$c + \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e+g) + \sum_{t=1}^{20} \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)\left(e_c + g_c + S\left(h_o, D\right) + c_o(h_o) - un(h_o)\right)(1-d)^t + \sum_t \sum_l p_N^l l[D(V(l) - f) + D^W(V^W(l) - f)](1 - d)^t$

Table 2: *Factory*, *utility* and *society* payoffs of six cases in Figure 1 (cont'd).

Case	***Factory* Payoff (Cost)**	***Utility* Payoff (Cost − Revenue)**	***Society* Payoff (Cost)**

4 C, H	$c - i + c_H + \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e+g) + \sum_{t=1}^{20} \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)\big(e_c + g_c + S(h_o, D) + c_o(h_o)\big)(1-d)^t + \sum_t \sum_l p_H^l\, lD(V(l)-f)(1-d)^t$	$K - \sum_t FK(1-d)^t - \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e+e^W) - \sum_{t=1}^{20} \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e_c + e^W)(1-d)^t$	$c + c_H + K - \sum_t FK(1-d)^t + \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e+g) + \sum_{t=1}^{20} \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)\big(e_c + g_c + S(h_o, D) + c_o(h_o) - un(h_o)\big)(1-d)^t + \sum_t \sum_l p_H^l\, l[D(V(l)-f) + D^W(V^W - f)](1-d)^t$
5 $B, \bar{H}$	$b - i + \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e+g) + \sum_l p_N^l lD(V(l)-f) + \sum_{t=1}^{20} \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)\big(e_c + g_c + S(h_o, D) + c_o(h_o)\big)(1-d)^t + \sum_{t=1}^{20} \sum_l p_N^l\, (g_c^b(l) + c_o(h_o))(1-d)^t$	$-\left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e+e^W) - \sum_{t=1}^{20} \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e_c + e^W)(1-d)^t$	$b + \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)(e+g) + \sum_l p_N^l l[D(V(l)-f) + D^W(V^W(l)-f)] + \sum_{t=1}^{20} \left(\frac{\sum_l p_N^l (M-l) + (1-\sum_l p_N^l)M}{M}\right)\big(e_c + g_c + S(h_o, D) + c_o(h_o) - un(h_o)\big)(1-d)^t + \sum_{t=1}^{20} \sum_l p_N^l\, [(g_c^b(l) + c_o(h_o) + lD^W(V^W(l) - f)](1-d)^t$
6 B, H	$b - i + c_H + \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e+g) + \sum_l p_H^l\, lD(V(l)-f) + \sum_{t=1}^{20} \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)\big(e_c + g_c + S(h_o, D) + c_o(h_o)\big)(1-d)^t + \sum_{t=1}^{20} \sum_l p_H^l\, (g_c^b(l) + c_o(h_o))(1-d)^t$	$K - \sum_t FK(1-d)^t - \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e+e^W) - \sum_{t=1}^{20} \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e_c + e^W)(1-d)^t$	$b + c_H + K - \sum_t FK(1-d)^t + \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)(e+g) + \sum_l p_H^l\, l[D(V(l)-f) + D^W(V^W(l)-f)] + \sum_{t=1}^{20} \left(\frac{\sum_l p_H^l (M-l) + (1-\sum_l p_H^l)M}{M}\right)\big(e_c + g_c + S(h_o, D) + c_o(h_o) - un(h_o)\big)(1-d)^t + \sum_{t=1}^{20} \sum_l p_H^l\, [g_c^b(l) + c_o(h_o) + lD^W(V^W(l) - f)](1-d)^t$

Table 3: Illustrative values for *factory*, *utility* and *society* payoffs of six cases in Figure 1

Case	***Factory* Payoff ($millions)**	***Utility* Payoff ($ millions)**	***Society* Payoff ($ millions)**
1 $\bar{C}, \bar{H}$	27.26 = 25.92 (energy cost) + 1.34 (outage cost)	−200.98 = −18.27 (*factory*) − 182.71 (other)	56.90 = 25.92 (energy cost) + 1.34 (outage cost for *factory*) + 29.64 (outage cost for other)
2 $\bar{C}, H$	26.20 = 25.93 (energy cost) + 0.17 (outage cost) + 0.1 (hardening cost to *factory*)	−200.05 = −18.28 (*factory*) − 182.77 (other) + 1 (hardening cost to *utility*)	30.80 = 25.93 (energy cost) + 0.17 (outage cost for *factory*) + 3.70 (outage cost for other) + 1 (hardening cost to *utility*)
3 $C, \bar{H}$	25.18 = 20.60 (energy cost) + 1.34 (outage cost) + 3.82 (CHP cost) – 0.59 (CHP incentive)	−195.12 = −12.41 (*factory*) − 182.71 (other)	54.95 = 20.60 (energy cost) + 1.34 (outage cost for *factory*) + 3.82 (CHP cost) + 29.64 (outage cost for other) – 0.45 (emission reductions)
4 C, H	24.11 = 20.61 (energy cost) + 0.17 (outage cost) + 3.82 (CHP cost) – 0.59 (CHP incentive) + 0.1 (hardening cost to *factory*)	−194.19= −12.42 (*factory*) − 182.77 (other) + 1 (hardening cost to *utility*)	28.85 = 20.61 (energy cost) + 0.17 (outage cost for *factory*) + 3.82 (CHP cost) + 3.70 (outage cost for other) + 1 (hardening cost to *utility*) −0.45 (emission reductions)
5* $B, \bar{H}$	23.97 = 20.60 (energy cost) + 3.95 (CHP cost) − 0.59 (CHP incentive)	−195.12 = −12.41 (*factory*) − 182.71 (other)	53.73 = 20.60 (energy cost) + 3.95 (CHP cost) + 29.64 (outage cost for other) − 1.16 (emission reductions)
6 B, H	24.07 = 20.61 (energy cost) + 3.95 (CHP cost) − 0.59 (CHP incentive) + 0.1 (hardening cost to *factory*)	−194.19 = −12.42 (*factory*) − 182.77 (other) + 1 (hardening cost to *utility*)	28.81 = 20.61(energy cost) + 3.95 (CHP cost) + 3.70 (outage cost for other) + 1 (hardening cost to *utility*) – 0.45 (emission reductions)

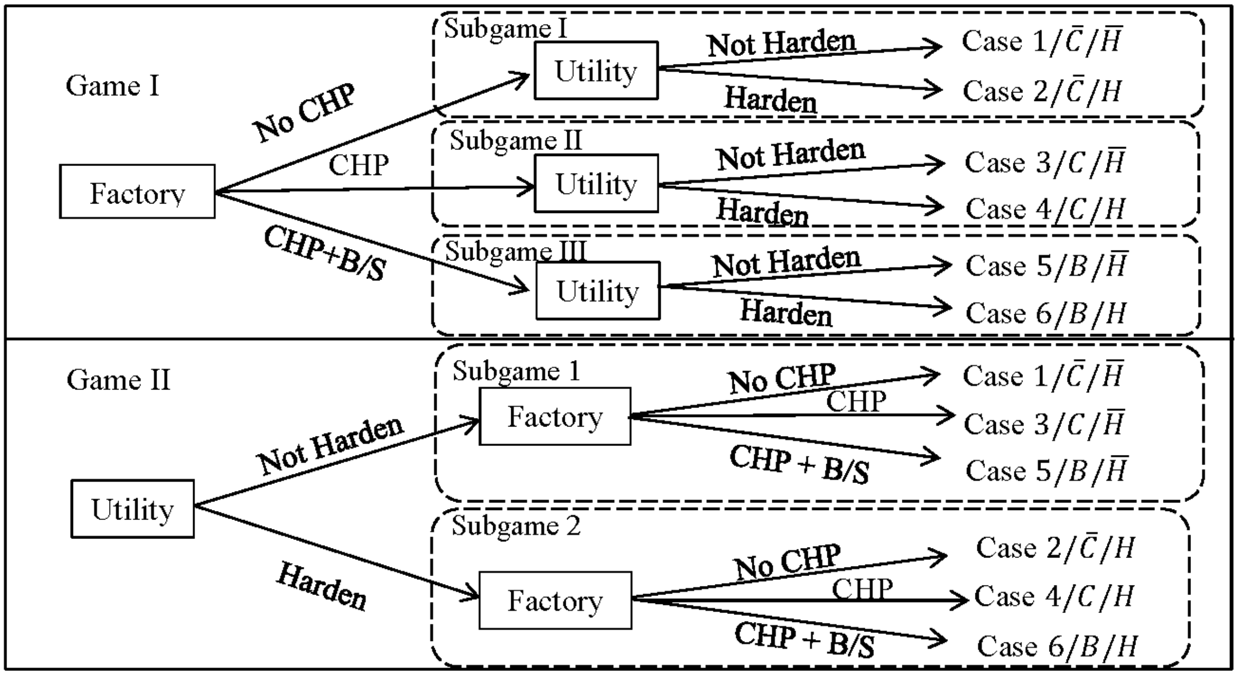

Figure 2: Game trees for Game I (*factory* decides first) and Game II (*utility* decides first)

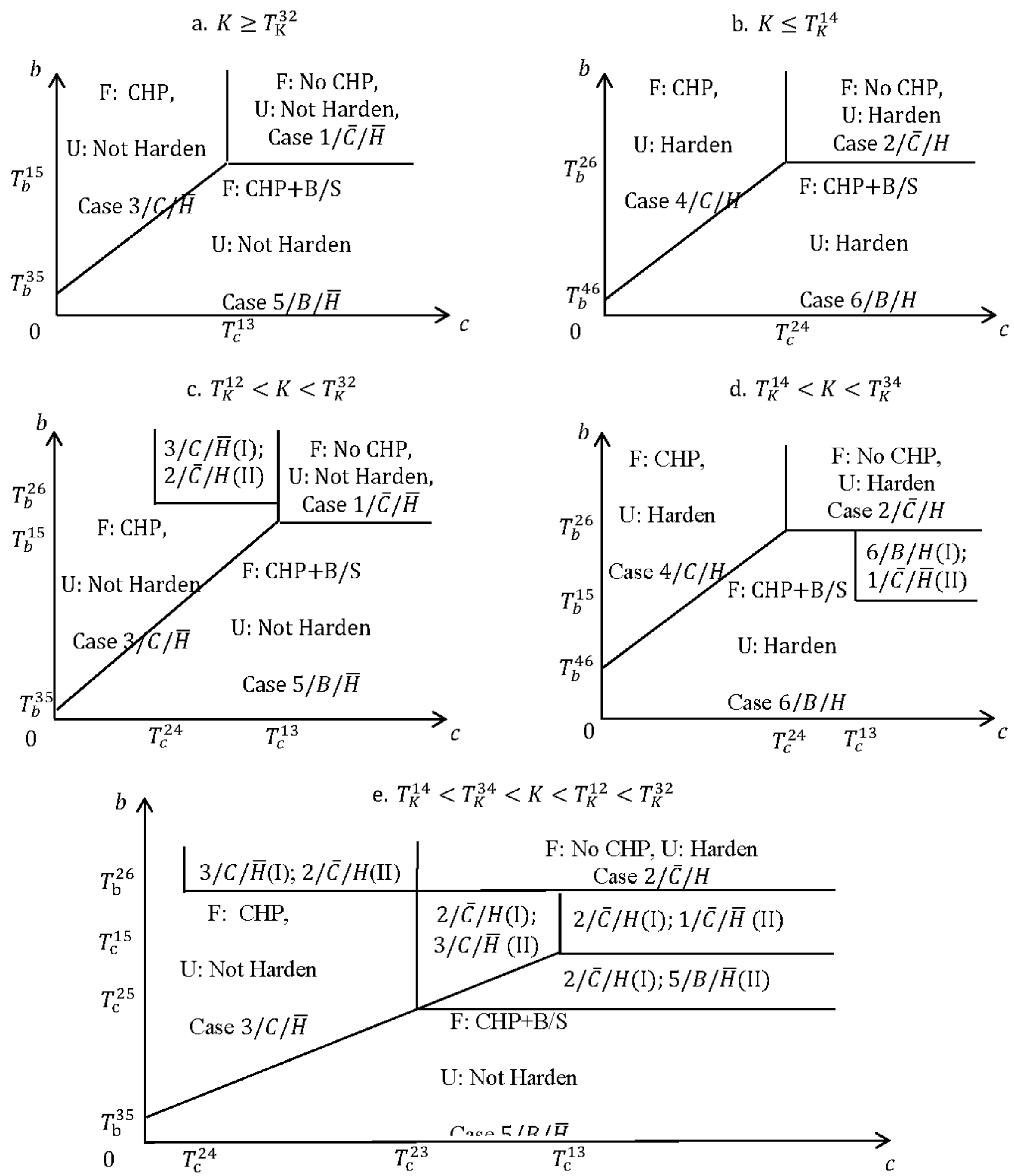

Figure 3: Analytical sensitivity analyses regarding costs of grid hardening, and CHP without and with blackstart capability.

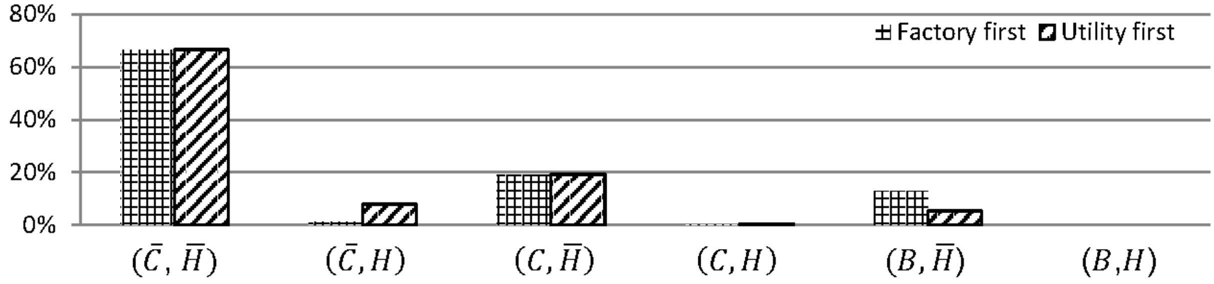

Figure 3: Frequency of six outcomes as optimal to games in Figure 1 from Monte Carlo simulation

Case 6/B/H. *Factory*: CHP+B/S, *Utility*: Harden

***Factory* Payoff (Cost):**

$$\overbrace{\underbrace{\left(\frac{\sum_l p_H^l(M-l)+\left(1-\sum_l p_H^l\right)M}{M}\right)}_{\text{(Prob. of Normal Operation)}} \underbrace{(e+g)}_{\text{(Energy Use without CHP)}} + \underbrace{\sum_l p_H^l}_{\text{(Prob. of Outage)}} \underbrace{lD(V(l)-f)}_{\text{(VOLL)}} + \underbrace{b+c_H}_{\text{(Capital Costs)}}}^{\text{Year 0}}$$

$$\overbrace{+\sum_{t=1}^{20} \underbrace{\left(\frac{\sum_l p_H^l(M-l)+\left(1-\sum_l p_H^l\right)M}{M}\right)}_{\text{(Prob. of Normal Operation)}} \underbrace{\left(e_c+g_c+S(h_o,\ D)+c_o(h_o)\right)}_{\text{(Energy\& OM Costs with CHP)}} \underbrace{(1-\mathrm{d})^{\mathrm{t}}}_{\text{(Discount)}} + \sum_{t=1}^{20} \underbrace{\sum_l p_H^l}_{\text{(Prob. of Outage)}} \underbrace{(g_c^b(l) + c_o(h_o))}_{\text{(Energy \& OM Costs with CHP at outage)}} \underbrace{(1-\mathrm{d})^{\mathrm{t}}}_{\text{(Discount)}}}^{\text{Year 1-20}}$$

***Utility* Payoff (Cost − Revenue):**

$$\overbrace{\underbrace{K-\sum_t FK(1-d)^t}_{\text{(Capital Costs with Overtime Return)}} - \underbrace{\left(\frac{\sum_l p_H^l(M-l)+\left(1-\sum_l p_H^l\right)M}{M}\right)}_{\text{(Prob. of Normal Operation)}} \underbrace{(e+e^W)}_{\text{(Electricity Tariff)}}}^{\text{Year 0}} \overbrace{+\sum_{t=1}^{20} \underbrace{\left(\frac{\sum_l p_H^l(M-l)+\left(1-\sum_l p_H^l\right)M}{M}\right)}_{\text{(Prob. of Outage)}} \underbrace{(e_c+e^W)}_{\text{(Electricity Tariff)}} \underbrace{(1-d)^t}_{\text{(Discount)}}}^{\text{Year 1-20}}$$

***Society* Payoff (Cost):**

$$\overbrace{\underbrace{\left(\frac{\sum_l p_H^l(M-l)+\left(1-\sum_l p_H^l\right)M}{M}\right)}_{\text{(Prob. of Normal Operation)}} \underbrace{(e+g)}_{\text{(Energy Use without CHP)}} + \underbrace{\sum_l p_H^l}_{\text{(Prob. of Outage)}} \underbrace{l[D(V(l)-f)+D^W(V^W(l)-f)]}_{\text{(VOLL)}} + \underbrace{b+c_H+K-\sum_t FK(1-d)^t}_{\text{(Capital Costs)}}}^{\text{Year 0}}$$

$$\overbrace{+\sum_{t=1}^{20} \underbrace{\left(\frac{\sum_l p_H^l(M-l)+\left(1-\sum_l p_H^l\right)M}{M}\right)}_{\text{(Prob. of Normal Operation)}} \underbrace{(e_c+g_c+S(h_o,D)+c_o(h_o)-un(h_o))}_{\text{(Gas\& OM Costs with CHP)}} \underbrace{(1-d)^t}_{\text{(Discount)}} + \sum_{t=1}^{20} \underbrace{\sum_l p_H^l}_{\text{(Prob. of Outage)}} \underbrace{[g_c^b(l) + c_o(h_o)+lD^W(V^W(l)-f)]}_{\text{(Gas \& OM Costs and VOLL at outage)}} \underbrace{(1-d)^t}_{\text{(Discount)}}}^{\text{Year 1-20}}$$

Figure 4: Illustration of different terms in typical payoff functions for *factory*, *utility* and *society*/government O&M Costs: Operation and maintenance costs including standby charges

Appendix

A.1 Explanation of two regulatory influences

Under Influence 1, (requiring *utility* to harden the grid when *factory* invests in a CHP), *factory* could voluntarily invest in a CHP because Case $4/C/H$ is guaranteed to solve Subgame II in Figure 1. Since $K < T_K^{12}$, Case $2/\bar{C}/H$ is the solution to Subgame I. Similarly, since $K > T_K^{34}$, Case $5/B/\overline{H}$ is the solution to Subgame III. The difference (Case $2/\bar{C}/H$ subtracts Case $4/C/H$) is $T_c^{24} - c$. If $c < T_c^{24}$, so Case $4/C/H$ is preferred over Case $2/\bar{C}/H$. Since Case $2/\bar{C}/H$ is preferred over Case $5/B/\overline{H}$ ($b > T_b^{25}$), therefore Case $4/C/H$ solves the whole game. By contrast, if Influence 2 does not require *factory* to invest a CHP+B/S but just requires *utility* not to harden the grid to avoid redundant investments, *factory* will not do so since Case $2/\bar{C}/H$ is preferred over Case $5/B/\overline{H}$ ($b < T_b^{25}$) by *factory*.

A.2 Explanations of requirements for two solutions in Section 3.5.2.

1. By definition, T_K^{34} is the benefit of hardening the grid to *utility* in increased electricity sales, given *factory* invests in a CHP. Similarly, T_K^{12} is the benefit of grid hardening to *utility* in increased electricity sales given *factory* does not invest in a CHP. Therefore, $T_K^{34} < T_K^{12}$ implies that the benefit of hardening the grid to *utility* is greater if *factory* does not invest in a CHP than if *factory* invests in a CHP.

2. $T_c^{24} - T_c^{23} = (Factory$ payoff in Case $3/C/\overline{H}) - (Factory$ payoff in Case $4/C/H)$ is the net benefit of hardening the grid to *factory* in terms of reduced VOLL given *factory* invests in a CHP. Therefore, $T_c^{23} < T_c^{24}$ implies the benefit of hardening the grid is greater than its cost given *factory* invests in a CHP. Due to space limitations, explanations for other four cases are omitted here, but are available upon request.

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